The Exact Sciences

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Three periods may be distinguished in the development of scientific research and teaching in France during the twentieth century: the years prior to 1914; the interwar period; and the balance of the century, from 1945. Despite the very different circumstances that prevailed during these periods, a certain structural continuity has persisted until the present day and given the development of the exact sciences in France its distinctive character.

The current system of schools and universities—public, secular, free, and open to all on the basis of merit—was devised by the Third Republic as a means of satisfying the fundamental condition of a modern democracy: the education of its citizens and the training of elites. Equality of opportunity was evidently an ideal that even today social forces have prevented from wholly becoming a reality; but it is nonetheless true that the French system of education has permitted many gifted students from modest backgrounds, notably through the award of scholarships, to reach the highest ranks of culture and science.

In this regard the fundamental role of the state in education and research is a constitutive and permanent feature of the French system, with very little committment of private and industrial enterprises. The French system is notable as well for the often close relationship between the scientific community and the political authorities, as much with respect to the agencies of the state (notably through the *grandes écoles*, which supply them with high-ranking civil servants) as, to a lesser degree, through the political involvement of academics and researchers and their service in governments, particularly during periods of reform. Prestigious scientists such as the mathematicans Paul Painlevé and Émile Borel and the physicists Irène Joliot-Curie and Jean Perrin have served as ministers before the Second World War and a number of others have been involved as well through the second half of the century.

Another abiding and well-known feature of the French system is the two-track system of universities and engineering *grandes écoles*, with their distinct personalities and courses of study. With the exception of a few of them, such as the École Supérieure de Chimie Industrielle (ESPCI), the École Polytechnique, and the Ecole Normale Supérieure (but that one had always a special status, being an integral part of the University system), the *grandes écoles* did not promote scientific research until the sixties.

The international scene in mathematics at the beginning of the twentieth century was dominated by a trio of French and German scholars: Henri Poincaré in Paris, and Felix Klein and David Hilbert in Göttingen. Other figures of importance included Vito Volterra in Italy, Jean-Gaston Darboux and Jacques Hadamard in France, and Hermann Minkowski in Switzerland. In France, the center of mathematical activity was the Académie des Sciences. The mathematicians who achieved notable advances at the end of the nineteenth century and the early part of the twentieth were for the most part graduates of the École Normale Supérieure, though a few (such as Poincaré and Camille Jordan) came from the École Polytechnique. On obtaining their degrees they were appointed to teaching positions in major provincial universities where they prepared their doctoral dissertations, subsequently returning to Paris to take up posts either at the Sorbonne (as in the case of Poincaré and, later, Émile Borel and Maurice Fréchet) or at the Collège de France (as in the case of Jordan, Hadamard, and Lebesgue). These tendencies were to continue for the most part in the decades that followed, though an increasing degree of influence came to be acquired by provincial universities and, after the Second World War, the Centre National de la Recherche Scientifique (CNRS) and the highly selective Institut des Hautes Études Scientifiques (IHES) in Bures-sur-Yvette.

The situation in mathematics at the turn of the century is well characterized by the papers presented at the Second International Congress of Mathematicians, held in Paris in 1900 on the occasion of the Universal Exposition. It was here that Hilbert famously proposed his twenty-three problems, which have stimulated research in mathematics through the present day. The influence of Henri Poincaré (1854-1912) was scarcely less considerable, in part because his mastery extended to practically every field of mathematics and mathematical physics. Commonly regarded as the last "universal mathematician," Poincaré sought always to grasp a problem in the most general terms, looking to detect straight away its central idea by a mode of thought that was chiefly intuitive and geometric, and examining its qualitative aspects before searching for particular solutions. At his death in 1912 Volterra wrote that deepening the domains that Poincaré had discovered would require the work of several generations of mathematicians—a prediction confirmed three-quarters of a century later by Jean Dieudonné, who observed that working out the implications of his thought had "occupied a good many of the mathematicians of the twentieth century."

Among Poincaré's contemporaries in France, Jean-Gaston Darboux (1842-1917) stands out for his contributions to the theory of differential equations, in analysis and theoretical mechanics, and for his teaching, which inspired one of the greatest of modern French mathematicians, Élie Cartan. And though Émile Picard (1856-1941) belongs, like Darboux, mainly to the nineteenth century, his role in creating algebraic geometry, in addition to his work on uniform and multiform analytic functions and functions of complex variables, was to be of lasting consequence.

Among the mathematicians of the succeeding generation, Paul Painlevé (1863-1933) achieved renown for his work on analytic functions and on algebraic curves and differential functions, with their singular points, the results of which he applied to problems of theoretical mechanics. Émile Borel (1871-1956), who wrote his thesis under Poincaré, investigated the theory of functions as well as the mathematical theory of measure, and made notable contributions to the mathematical theory of probability that were subsequently to be exploited by A. N. Kolmogorov. Jacques Hadamard (1865-1963) did important work on a variety of topics, among them integral equations and the analytic theory of numbers, and is also remembered for his classic work *The Psychology of Invention in the Mathematical Field* (1945).

The theory of functions of one or more real variables pioneered by Camille Jordan (1838-1922) led Borel and, later, Henri Lebesgue (1875-1941)—both inspired, like their colleague Louis-René Baire (1874-1932), by Cantor's theory of sets—to develop their respective conceptions of measure ("Borel measure" and "Lebesgue measure"). In a series of papers published between 1903 and 1910, Lebesgue used this notion to elaborate his now-classical theory of integration, which met with great resistance at first, but whose power to unify whole branches of mathematics, by resolving a number of difficulties encountered in the work of Riemann and Weierstrass, gradually came to be recognized. In 1908, Maurice Fréchet (1878-1973), building on Lebesgue's work, introduced the notion of an "abstract space" whose elements are more abstract than functions (a notion that shortly afterwards was to lead to Banach and Hilbert spaces, the latter being successfully applied in quantum mechanics). Arnaud Denjoy (1884-1974) obtained notable results for problems associated with a range of fields, including the theory of functions of real variables, topology, and trigonometric series, and proposed a generalization of Lebesgue's integral. Additionally, his work on quasi-analytical functions was a source of inspiration for Benoît Mandelbrot's research on fractals.

Élie Cartan (1869-1951) was among the most profound mathematicians of his time, and his influence upon contemporary mathematics now appears crucial; yet although his talent had been recognized at once by Poincaré and Hermann Weyl, the originality of his work was not generally appreciated before the 1930s. Cartan displayed a rare aptitude for seeing connections between different domains of mathematics and, like Poincaré, invented new methods. His early work demonstrated and extended the local theory of Lie groups. He went on to do extensive research on differential manifolds, one of the principal areas of twentieth-century mathematics, which he was among the first to develop around the theory of groups, combining the theory of partial differential systems and differential geometry. In 1913 he discovered spinors (a mathematical magnitude later commonly used in general relativity and quantum theory) and, using the classification of simple Lie groups, created the theory of symmetrical Riemannian spaces, which have applications in the most varied domains of mathematics, including automorphic functions (previously posited and studied by Poincaré) and analytic number theory.

Cartan also introduced topological methods for the global properties of Lie groups, invented the calculus of exterior differential forms, and created the notions of "fiber" (later one of the most important in mathematics) and "connection," which he applied to various domains of analysis and geometry. He introduced and developed the study of four types of space on which a connection can been defined (Euclidean, affine, conformal, and projective), developing a geometry more general than that of Riemann that included torsion in addition to curvature and whose applications in general relativity he studied together with Einstein.

Though French mathematicians had managed to uphold a tradition of excellence, there were signs that the discipline (with the exception of Cartan's work) was failing to keep up with new tendencies that were changing the very nature of mathematics, both at home and abroad, pushing it in the direction of greater abstraction and formalism. In France these tendencies were to be united under the collective pseudonym Nicolas Bourbaki.

Bourbaki was the name chosen to disguise the activity of a group of young mathematicians at the École Normale Supérieure in the late 1930s who sought to arrest what they saw as the decline of French mathematics. What began apparently as an idle hoax rather quickly became a serious and systematic attempt to modernize the teaching of mathematics at the university level in France and, in a deliberate break with the "intuitive" methods of the past, to establish the discipline on a rigorous basis. The work of this group, which included some of the most gifted mathematicians of their generation, was subjected to the severe criticism of its members and polished through meetings and seminars. The first volume of their joint effort, published anonymously by "the association of the collaborators of Nicolas Bourbaki," appeared under the title *Eléments de mathématiques* in 1939. Twenty-four volumes followed over the next two decades (along with revised versions that continued to appear into the 1970s), augmented from 1948 onward by thirty-eight volumes of seminar proceedings.

The group's first members included Henri Cartan (b. 1903, son of Élie Cartan), Jean Leray (b. 1906), Claude Chevalley (1909-1984), Jean Dieudonné (1906-1992), and André Weil (1906-1998), each of whom produced a remarkable body of work on his own account. Cartan's research concerned algebra and algebraic topology, the theory of functions of real and complex variables, partial derivative equations, and potential theory. Leray worked on algebraic topology, spectral series and the notion (which he invented) of a "bundle" of planes, and partial derivative equations (together with solutions to them that are not derivable in the usual sense). Dieudonné produced important results in general topology, the theory of topological vector spaces, group theory, and algebraic geometry, as did Chevalley and Weil in algebraic geometry, algebra, number theory and Lie groups. Jacques Herbrand (1908-1931), a brilliant young mathematical logician who met an unfortunately early death, was closely associated with the group as well.

The *Eléments de mathématiques* was laid out in axiomatic fashion (in the spirit of Euclid, as the title suggests, and Hilbert's *Grundlagen der Geometrie*) in nine books (of which some were treated in several volumes) on as many subjects: set theory—this being the basis for all the others—algebra, general topology, functions of a real variable, topological vector spaces, integration, commutative algebra, Lie groups and algebras, and differential and analytic manifolds. The entire twenty-five volumes of the *Eléments* amounted to a thoroughgoing reorganization of mathematics, which in turn made its unity manifest.

The avant-garde work of the group's founders, and the impression it made upon new members through the seminars they conducted, almost completely rearranged the French mathematical landscape, with the result that the Bourbaki school left its mark upon all of the nation's research institutions and universities. At the same time its international influence was considerable. It must be said, however, that the consequences of the "modern mathematics" movement it inspired, which sought to impose an abstract and axiomatic conception of the teaching of mathematics down to the secondary-school level, were sometimes catastrophic, preventing younger students from developing a capacity for intuition and creativity.

After 1945 a second generation of Bourbaki mathematicians appeared, not less exceptional than the first—among them the first French winners of the Fields Medal (the equivalent in mathematics of the Nobel Prize). Laurent Schwartz (b. 1915) developed the theory of generalized functions, or "distributions." The research done by Jean-Pierre Serre (b. 1926) in algebraic topology, building on the work of his teacher Henri Cartan and Jean Leray, led to the renewal of a fundamental branch of mathematics, established in its modern sense by Poincaré in 1895, which includes homology and algebraic computations on the subspaces of a given space. The very deep work done by Alexandre Groethendiek (b. 1928) on the foundations of algebraic geometry produced a sort of revolution in this field, raising it to a new level of abstraction with the aid of new and complex concepts, while nonetheless making it possible to obtain surprising results in both algebraic geometry and number theory.

Successive generations have likewise brought forth an impressive number of brilliant mathematicians, among them—to mention only Fields medalists—Pierre Deligne (b. 1944), who brought to bear the full resources of algebraic geometry in proving a conjecture by André Weil concerning the zeta function; Alain Connes (b. 1947), honored for his application of functional analysis to von Neumann algebras and his work on non-commutative differential geometry; Jean Bourgain (b. 1954), noted for his work on linear functional analysis, harmonic analysis, and ergodic theory; Pierre-Louis Lions (b. 1956), a specialist in the theory of partial differential equations in relation to the theory of kinetic equations and the theory of viscosity solutions; and Jean-Christophe Yoccoz (b.1957), whose research has concerned the theory of dynamical systems and holomorphic dynamics.

By contrast with the separation of mathematics—conceived in the purely abstract manner of Bourbaki—from physics (a separation that was not, however, altogether absolute: Schwartz's theory of distributions, for example, took its point of departure from the Dirac delta function in quantum mechanics), the years since 1960 have witnessed a return to the tradition of reciprocal exchange and cross-fertilization between mathematics and mathematical physics, indeed theoretical physics itself. This return is illustrated by the importance attached to qualitative and topological approaches, the theory of dynamical systems (inspired by Poincaré's work in the late nineteenth century on the three-body problem in celestial mechanics and on curves defined by differential equations), and the various theories ("gauge," "supersymmetry," and "string") of contemporary quantum physics. Catastrophe theory, due to René Thom (b. 1923); dynamical systems theory; the non-commutative geometry developed by Connes; the work of Lions in applied mathematics, probability and statistics—all these are rich and original contributions to an ancient tradition, posing once again the perennial question of the nature of the singular relation that obtains between mathematics and physics.

It has sometimes been said that French physicists were absent from the revolutions in physics that took place during the first decades of the century, remaining stuck in the past, unresponsive to the new ideas that were taking shape. The assertion contains an element of truth, in the sense that few of these physicists turned away from their customary subjects of research: for some, general mechanics; for others, visible radiation and optics—two classic paths of research in physics in France, traditional since the eighteenth century in the case of mechanics and associated with the names of Lagrange and Laplace; and since the nineteenth century in the case of optics, Fresnel, Fizeau, and several others having created a tradition that was as much mathematical as experimental.

Even so, French scientists contributed in a number of areas to the new physics: radiation and atomic properties, in which two generations of the Curie (later Joliot-Curie) family excelled until the Second World War; atomic and molecular physics, with the work of Jean Perrin (1870-1942); electromagnetism and electrodynamics, with Poincaré and Paul Langevin (1872-1946); the theory of magnetism, with Langevin and Pierre Weiss (1865-1940), and later Léon Brillouin (1889-1969); the implications of Einstein's theory of relativity, chiefly with Langevin, but also Élie Cartan; quantum physics in its early stages, with a penetrating view of the import of this novel approach for the foundations of physics itself being given by Poincaré and Langevin, and contributions (delayed by the First World War) made by Brillouin and Edmond Bauer (1880-1963).

The main avenues of research in physics at the beginning of the century were those of experimental physics, in the traditional areas of mechanics and optics. Work in theoretical physics done by physicists (rather than by mathematicians, from the perspective of pure mathematical physics) was the exception: here again one thinks of Henri Poincaré (in his role as a physicist concerned with physical phenomena) and Langevin, as well as Pierre Curie (1859-1906) and Marcel Brillouin (1854-1948, father of Léon) in physics; and Pierre Duhem (1861-1916) and Henry Le Chatelier (1850-1936) in physical chemistry and thermodynamics. Apart from the work of these figures, the de facto division that existed with regard to research—between mathematical physics, on the one hand, and a physics conceived as essentially experimental in nature—ruled out any truly systematic attempt to reorganize a body of knowledge in both formal and conceptual terms. The approach to the new physics adopted by those French physicists who worked in it, closely allied with experiment and more or less independent of existing theory, was rather direct and proceeded by two paths: the molecular properties of matter, dominated by the work of Jean Perrin; and the study of new forms of radiation, known as radioactivity, led for two generations by the school of the Curies.

Perrin's work on molecular motion, which studied colloidal suspension in liquids in a series of experiments carried out between 1908 and 1913, verified Einstein's 1905 calculations (done on the basis of kinetic theory and statistical mechanics) and made it possible to conclusively demonstrate the physical existence of atoms and to determine molecular dimensions. The Brownian movement of colloidal particles in suspension is the result of the impact upon them by the molecules of the surrounding medium. Perrin's analysis allowed him to count the number of molecules in a given volume and so measure, in a strict sense, the Avogadro number. In recognition of this achievement he was awarded the Nobel Prize for physics in 1926.

Shortly after Röntgen's discovery of x-rays in 1895, Henri Becquerel (1852-1908) detected the emission of penetrating radiation in uranium salts—a phenomenon named "radioactivity" in 1898 by Marie Sklodowska-Curie (1867-1934), who studied it systematically in conjunction with her husband, Pierre Curie. The first scientist to win the Nobel Prize twice (in physics in 1903, with Becquerel and Pierre Curie, and then in chemistry in 1911), Marie Curie devoted herself after her husband's death to the chemistry of radioelements as well as to the industrial production of radioactive sources and to medical applications. Her eldest daughter, Irène Joliot-Curie, and her son-in-law Frédéric Joliot, took over from her in the first and third of these areas while also going back to fundamental physics. In general, the prestigious French school of radioactivity can be said to have been more concerned with experiment and technology than with theory, and, at least in its early phases, free from the institutional elitism embodied by the École Normale Supérieure, the Sorbonne, and the École Polytechnique.

From the theoretical point of view, physics was revitalized in the early twentieth century by two great challenges to orthodox thinking: the theory of relativity and quantum theory. Independently of each other—but, initially, in parallel—they furnished the conceptual framework necessary for the understanding of new phenomena.

The special theory of relativity grew out of problems encountered by the electromagnetic theory of bodies in motion, or electrodynamics, which lay at the juncture of Maxwell's electromagnetic theory and Newtonian mechanics. These problems—tackled by various authors after Maxwell, including H. A. Lorentz and Heinrich Hertz—were solved, on the basis of Lorentz's first attempt, in two ways: through the dynamical arguments advanced by Lorentz and Poincaré (in 1904 and 1905, respectively), which established a relativistic electrodynamics; and Einstein's inquiry into the fundamental physical principles that form the basis of electrodynamics and mechanics, modifying the concepts of space and time inherited from classical mechanics and thus obtaining a new relativistic kinematics that led to the desired modification of dynamics. The implications of the two theories for dynamics were the same, since both posited relativistic invariance (for inertial motions) and the invariance of the speed of light—that is, a constant and absolute upper limit for all motions; but the structure of the two theories, and their analysis of the fundamental concepts, were vastly different.

Paul Langevin also took part in the investigations into electrodynamics and the relativity of motion, and subsequently played a preponderant role in the diffusion and teaching, both in France and at the international level, of the new theory in its special and general form alike. Additionally, he took an interest in optics and in experiments aimed at describing the motion of the earth (in this he was an heir, like Poincaré, to the tradition of Fizeau and Mascart). With regard to electromagnetism, he developed a model of the electron in motion contracted with constant volume, though, as Poincaré remarked in 1905, it had the defect of not respecting the principle of relativity. In 1904-1905 he conceived the notion of "energy inertia," by generalizing a property of the electron that flowed from the variability of its "electromagnetic mass" in relation to speed, which led him to write down the famous formula $E = mc^2$. When, at the beginning of 1906, he found it expressed in a still more general manner in a paper by Einstein, as part of a theory that seemed to him wholly satisfactory, he embraced this theory and shortly thereafter began to teach it at the Collège de France. Nonetheless he remained faithful to his own conception of a dynamical ether, albeit one devoid of properties, until the appearance around 1914 of Einstein's first papers sketching a generalized theory obliged him to speak of a "field" unsupported by an ether. During this period Langevin's ideas occupied a sort of intermediate position between those of Poincaré (advanced on behalf of an electromagnetic dynamics) and those of Einstein (arguing for a theory of relativistic invariance, or covariance).

Langevin's lectures on the theory of relativity influenced many of the leading figures in French mathematics, notably Élie Cartan and Émile Borel, but also physicists such as Louis de Broglie (1892-1987), who drew upon it to make original contributions beginning in the early 1920s. In 1922 Cartan formulated his theory of "absolute parallelism" in connection with Einstein's theory of general relativity and the question of the unification of gravitation and electromagnetism, and a few years later personally studied these matters with Einstein. And in 1923 de Broglie used the theory of special relativity in his reasoning towards discovering the general relation associating particles with waves.

As in the case of the theory of relativity, the physics of quanta, if it was not actually ignored by French physicists, long remained marginal to their research and was wholly disregarded by university curricula until the end of the Second World War. The theoretical and experimental advances of the "new physics," up until Einstein's first ("semi-classical") statement of the theory in late 1916, were made for the most part in Germany, in Great Britain, in Denmark and in the Netherlands. In the absence of a genuinely physical theory, French participation in research into the quantum structure of matter and radiation in the early part of the century was bound to be slight: experimental physicists in France, following a distinguished and well-established tradition, were content to work instead on the new forms of radiation as well as problems in optics and spectroscopy.

And yet this would not be an altogether picture if one omitted to mention Langevin's interest in non-classical phenomena of radiation and atomic physics, expressed first in his lectures at the Collège de France in 1908, then in 1911-1912 and regularly thereafter, as well as the research carried out by Edmond Bauer and Léon Brillouin, students of Langevin and Perrin, whose doctoral theses treated quanta at least in part. It is worth to rmention the arguments advanced by Langevin and Poincaré at the first Solvay Conference in 1911 and after, respectively in 1912 and 1913, with regard to the quantum "discontinuity" which Planck himself wished to reduce, contrary to Einstein. Poincaré was led to demonstrate rigorously from the theoretical point of view that the hypothesis of quantum discontinuity was indispensable, and drew the fundamental conclusion that, contrary to the standard practice of physics for two centuries, phenomena occurring on very small scales could no longer be represented by differential equations—thus anticipating all the difficulties that would arise more than a decade later in the interpretation of quantum mechanics.

As for Langevin, he laid stress on the role of probability. He saw that Einstein's notion of the "probability of a state in time," far from appealing to a particular theory such as statistical mechanics, constituted instead an independent tool for investigating the atomic world and radiation that was inaccessible to the senses. This insight enabled him very quickly to grasp the profound meaning of the conceptions of quantum mechanics when they were proposed fifteen years later. Once detached from the combinatory computations of statistical mechanics, probability relations could obey new rules, among them the indistinguishability of identical particles that would later be seen to lie at the heart of Planck's quantum of action.

The effect of Poincaré's and Langevin's exceptionally acute remarks at the first Solvay conference was to announce the second period of quantum physics, devoted to the elaboration and interpretation of an adequate theory. If French physicists remained on the whole strangers to this enterprise, several exceptions need nonetheless to be noted, in particular the considerable contribution made by Louis de Broglie in 1923, associating, for every particle, a frequency with its energy and a wave length with its momentum or quantity of motion, and thus apply the generalization of wave-particle duality, proposed for light by Einstein in 1916, to elements of matter such as electrons. The hypothesis was verified experimentally several years later with the demonstration that electrons display a diffraction effect similar to that of light. Here, as on other occasions, Langevin (who directed de Broglie's thesis) played a crucial role: he solicited the opinion of Einstein, who recognized the importance of the work (converging as it did with his own research with the Indian physicist Satyendra Nath Bose, which was to produce the notions of indistinguishability and quantum statistics) and communicated it to Erwin Schrödinger, who shortly afterwards made it the pivotal element of his wave mechanics.

Although the interwar period did not witness the rise of a French school of quantum mechanics, in spite of de Broglie's exceptional breakthrough, the contributions of several physicists need nonetheless to be mentioned—Jacques Solomon (1908-1942), Francis Perrin (1901-1992, son of Jean), and Alexandre Proca (1897-1955)—in addition to those of Bauer and Brillouin, who carried on with their earlier research. The heuristic effect of Langevin's work needs also once again to be recalled, both on the national and the international level (Langevin was named by his peers to succeed Lorentz as scientific secretary of the Solvay Conference on the latter's death in 1928), as well as his incisive interventions in the debate over the interpretation of quantum mechanics, which represented a sort of intermediate position between the views of Einstein and those of Bohr.

It was only after the Second World War that theoretical physics, particularly quantum physics, reached maturity in France.. A number of young French physicists trained at the École Normale Supérieure and the École Polytechnique—including Maurice Lévy (b. 1922), Bernard d'Espagnat (b. 1921), Louis Michel (1923-1999), Albert Messiah (b. 1921) and a few others—were sent abroad for postgraduate work to Copenhagen, Manchester, and the United States, and it was owing to them that quantum mechanics came to be taught in French universities and that theoretical research in quantum physics began to develop in the atomic, nuclear, and subnuclear domains.

In atomic physics and quantum optics, Alfred Kastler (1902-1994) devised the method of "double resonance" in collaboration with his student—later colleague—Jean Brossel (b. 1918) in 1949-1950. Applied to the fundamental states of atoms, it enabled him shortly thereafter to discover optical pumping. This phenomenon, based on a property of transitions between atomic levels remarked upon from the theoretical point of view by Einstein in 1916 ("stimulated emission"), made it possible to accumulate atoms in excited states at a given level. Kastler's results subsequently led to the invention of maser amplifiers and laser sources and, in 1966, a Nobel Prize.

The Kastler-Brossel laboratory at the École Normale Supérieure subsequently emerged as one of the leading centers for physics and quantum and atomic optics, where the most advanced experimental research (cooling atoms to extremely low temperatures using laser bundles, electromagnetic trapping and so on) was accompanied by theoretical developments, notably in quantum electrodynamics. Thus the team led by Claude Cohen-Tannoudji (b. 1933), a specialist in the quantum electrodynamics of atoms ”dressed” by photons, and winner of the Nobel Prize in 1997, succeeded in cooling atoms to temperatures that differed from absolute zero by only a millionth—even a billionth—of a degree, and to individually isolate them by magnetic trapping. This made possible not only the construction of atomic clocks that are the most stable in the world, but also the detection of elementary and fundamental quantum phenomena, long ago predicted but not observed until very recently, among them Bose-Einstein condensation, and quantum decoherence.

It was also in association with the Kastler-Brossel laboratory, at the Institut d’Optique d’Orsay, that Alain Aspect (b. 1947) and his colleagues conducted an exceedingly precise, and therefore decisive, experiment that constituted a test of quantum mechanics in a hitherto-inaccessible domain: entangled quantum systems separated by great distances. A theorem of quantum physics proven by J. S. Bell in 1964 showed that the hypothesis of locality, or local separability, of quantum sub-systems that are spatially separate after having initially been correlated (as, for example, in the case of two photons emitted by the same atom), implied contradictory inequalities with the correlations that were strictly required by quantum mechanics. The possibility of maintaining local separability (formerly considered optional, depending on the interpretation of quantum mechanics chosen) therefore had to be decided by experiment. Aspect’s experiments on photons correlated at a distance (now able to be studied more precisely with the aid of lasers) made it possible to demonstrate the non-locality, or local non-separability, of quantum systems, and therefore the increased validity of quantum mechanics.

Important work has been done in a number of related fields in France since 1945. In particle physics, the study of elementary particles with visual detectors (bubble chambers), leading to important results (“neutral weak currents”), and the invention by Georges Charpak (b. 1924) of an original and efficient electronic particle detector having a range of useful applications in biology and medicine as well as in physics won him the Nobel Prize in 1992. In condensed matter physics, Pierre Gilles de Gennes (b. 1932) received the Nobel Prize the year before for his research on phase changes, superconductivity, and liquid crystals. The mathematical theory of non-linear dynamical systems, whose roots are to be found in the work of Poincaré, has rather recently been related to a variety of physical and other phenomena known as “chaotic” systems through the research of the Belgian physicist and mathematician David Ruelle (b. 1935), who works in France at IHES. In chemistry, Jean-Marie Lehn (b. 1939) won the Nobel Prize in 1987 for his analysis of molecular recognition and corresponding synthesis of hollow molecules, not found in nature, that display a great variety of three-dimensional geometrical forms, work that gave birth to the new field of supramolecular chemistry. And in astrophysics, whose various branches include the structure and evolution of the universe, the work of Evry Schatzman (b. 1920) on the internal processes of star-formation has greatly influenced work both in France, where a younger generation of astrophysicists now works in close collaboration with subatomic physicists, and abroad.

Further Reading

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